HIGH-SPEED, HIGH-RESOLUTION FOCAL PLANE ARRAY IMAGING SYSTEM

FINAL TECHNICAL REPORT

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14. ABSTRACT

We have developed a high-resolution, high-speed InSb Focal Plane Array Imager which was built and delivered by Indigo Systems, Inc., of Santa Barbara, CA for use in research and development of thermal wave imaging and nondestructive inspection (NDE) aircraft structures. The design team included Indigo Engineers and faculty from Wayne State. The imager was designed with features intended specifically for use in hangar and field conditions. It includes a sunlight readable monitor, and a 50 foot cable for remote operation. Furthermore, facilities are provided at the camera end of the cable for control of the image acquisition of the computer, so that it can be used as a single-operator system. The camera itself has a very fast, large-area focal plane array (640 x 512 pixels), a 14-bit dynamic range digitizer, and is capable of acquiring image data a rate of 40 Mpixels/s. The dynamic range can be extended even further by use of a novel switchable array integration time.

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Executive Summary

We have developed a specially designed, next-generation, high-resolution, high-speed InSb Focal Plane Array Imager which was built and delivered by Indigo Systems, Inc., of Santa Barbara, CA for use in research and development of thermal wave imaging and nondestructive inspection (NDE) of metal and composite aircraft structures. The design team included Indigo Engineers and faculty from Wayne State. The imager was designed with features intended specifically for use in hangar and field conditions. It includes a sunlight readable monitor, and a 50 foot cable for remote operation on step ladders, lifts, etc. Furthermore, facilities are provided at the camera end of the cable for control of the image acquisition of the computer, so that it can be used as a single-operator system. The camera itself has a very fast, large-area focal plane array (640 x 512 pixels), a 14-bit dynamic range digitizer, and is capable of acquiring image data a rate of 40 Mpixels/s. The dynamic range can be extended even further by use of a novel switchable array integration time. All of the pixels in the array integrate at the same time, so that the camera acts in a snapshot mode. Illustrative examples of NDE applications for which the camera will be used are presented – one for corrosion detection and measurement, a second for small crack detection.

Introduction

In our original request, we proposed to purchase a next-generation, high-resolution, high-speed InSb Focal Plane Array Imager for use in research and development of thermal wave imaging and nondestructive inspection of metal and composite aircraft structures. The basic imager was to have been based upon the Raytheon ResolveIR camera, then currently under development. We further proposed to tailor the imaging system for ultimate DoD applications. A total cost estimate for the system was originally \$287,600, of which \$71,900 was to be cost-shared from non-federal funds. Subsequently, we modified this budget to a total request of \$215,100, with \$110,000 requested from AFOSR/DURIP funds.

Upon receiving notification of funding from AFOSR, we contacted Raytheon Amber, and discovered that the company had moved from Goleta, CA to Texas, with a loss of a large number of their specialized IR camera development engineering staff, and thus was unable to support the development of their new, state-of-the-art ResolveIR camera. Fortunately, most of engineering staff with whom we had technical interactions joined another company in the Goleta area, Indigo Systems, Inc., and were able to assist that company in the development of a camera that would meet or exceed our original specifications. Clearly, this change of vendors and the associated development of a new set of detailed camera specifications caused some delay in the construction of our system. First, we arranged for several meetings with Indigo engineers, both at their facility in California, and at the facility of their partner company in Kentucky, Lumitron. These meetings were to determine the final design of the system, and to delegate areas of responsibility for subsystems. It should be noted also that the design incorporated a brand new large-format (640x512) InSb array, as well as interface electronics that were newly and expressly designed for thermal wave imaging applications and thus were to be packaged with the power supply and most of the interface electronics separated from the camera head by a 50-ft cable. This design results in a very light weight camera head. Furthermore a special on-board cryogenic cooler was chosen so as to maintain the lowest weight. Specialized electronics were designed during our meetings to accommodate thermal wave imaging needs, such as triggering in and out to provide strict synchronization and timing of the images with external stimuli. The designs incorporated a

brand-new capability to provide for a change in detector integration time during the acquisition of a sequence of thermal wave images, and to permit a wider dynamic range of digitization of the data. Based upon our group's previous experience in field operations, we have incorporated a sunlight flat-screen monitor, so that the system can be used in both hangar and ramp operations, with no need to provide shade for the operator to be able to view the data clearly.

Whereas the original projection of the Indigo/Lumitron team (see Appendix) was for a delivery of the system to Wayne State prior to the end of November, 1999, there were several unavoidable delays caused by their sub-vendors – namely, the foundry which was selected to produce the large format FPA chip, and the supplier of the cryogenic cooler – this schedule was successively delayed to an August, 2000 delivery. Consequently, our Final Report will be restricted to a description of the system as delivered, together with a description of our intended applications of the system for crack detection and the detection of hidden corrosion on aircraft structures. On the basis of our prelimary results using older IR camera technology, we are confident that this state-of-the-art IR imaging system will make a major contribution to the advancement of inspection methodologies for DoD and civilian applications, both aerospace and others. Furthermore, since this camera system was specifically designed from the ground up for NDE, the AFOSR investment, in collaboration with Wayne State, will undoubtedly lead to a commercially viable system for use in a wide range of industrial and military NDE applications.

Description of the Instrumentation

A closeup photograph of our new large format camera head is shown in Fig. 1. Depending on the particular IR lens in use for a given application, this camera head weights 5-7 pounds. This light weight was accomplished by using a remote power supply, together with a cable which can be up to 50 feet long. This combination of remote power supply and light weight was specifically designed for use in hangar and ramp applications. It represents a prototype of the first commercial camera that was designed from the ground up for such aerospace inspection applications.

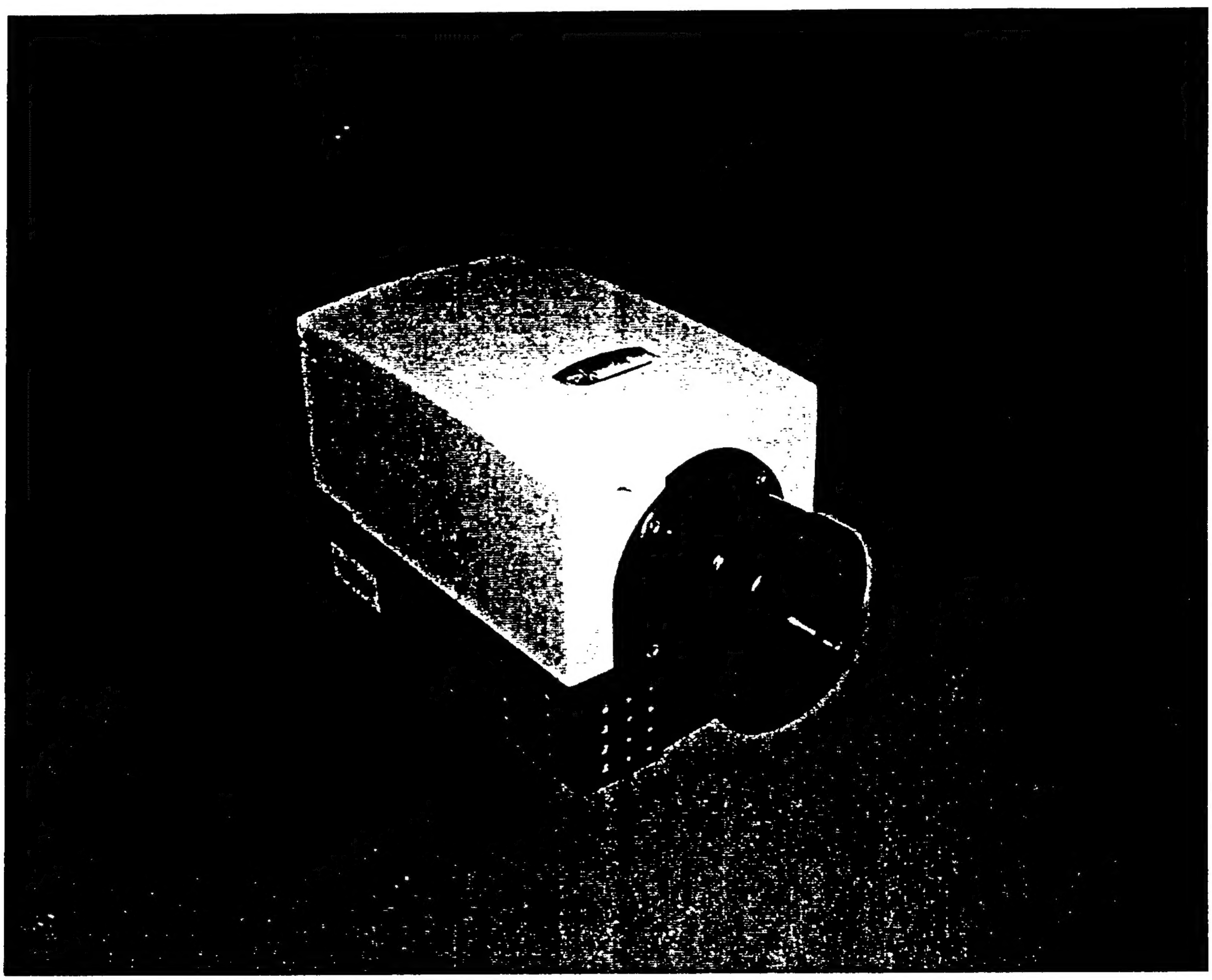


Fig. 1 Photograph of our new large format camera head

In Fig. 2, we show the camera, together with its computer control system, in a shock-mounted enclosure which is designed to be a self-contained shipping case. The computer is built into a standard rack mount, and the display, which is also rack-mounted, is a "sunlight" LCD monitor, both for ease of shipment, and for excellent visibility under field conditions, where shade is often unavailable. A photograph of the system is shown in Fig. 3, stored in its enclosure, with the monitor and keyboard stowed, and the enclosure cover about to be mounted for shipment.

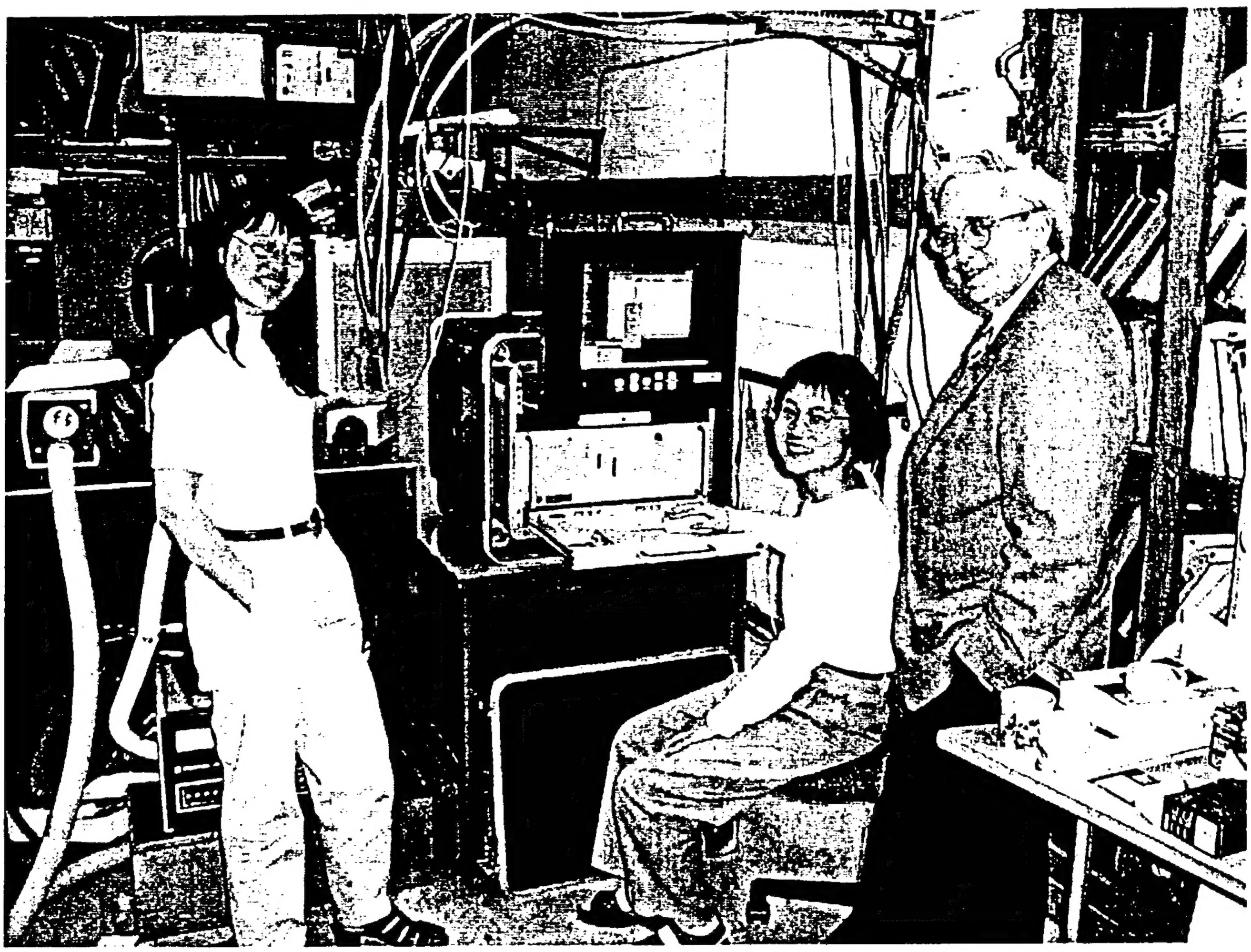


Fig. 2 Photograph of Profs. Han (left) and Thomas (right), together with postdoctoral Research Associate Ouyang (center), with the new IR imaging system in the Thermal Wave Imaging Lab at Wayne State University. The "sunlight" monitor is shown in the open position, with the rack-mounted computer keyboard open for operation. The camera head is on the left, on top of the optical table.

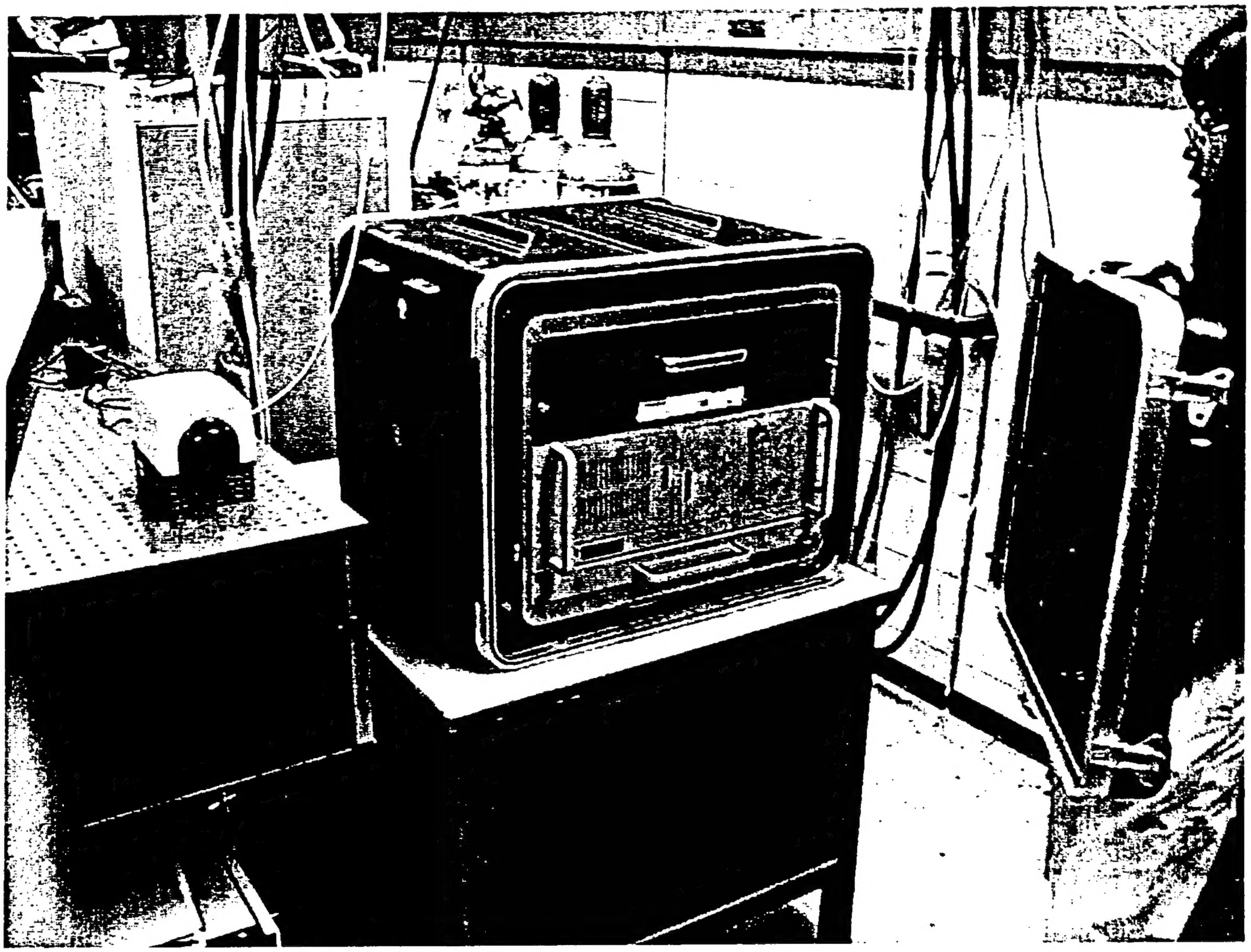


Fig. 3 Photograph of the IR imaging system, stored in its enclosure, with the monitor and keyboard stowed, and the enclosure cover about to be mounted for shipment.

In Fig. 4, the system is shown packed and ready for shipment, with camera in its shipping case, which can be hand-carried for safety. In the following sections, we illustrate some of the applications for which this new system has been designed.

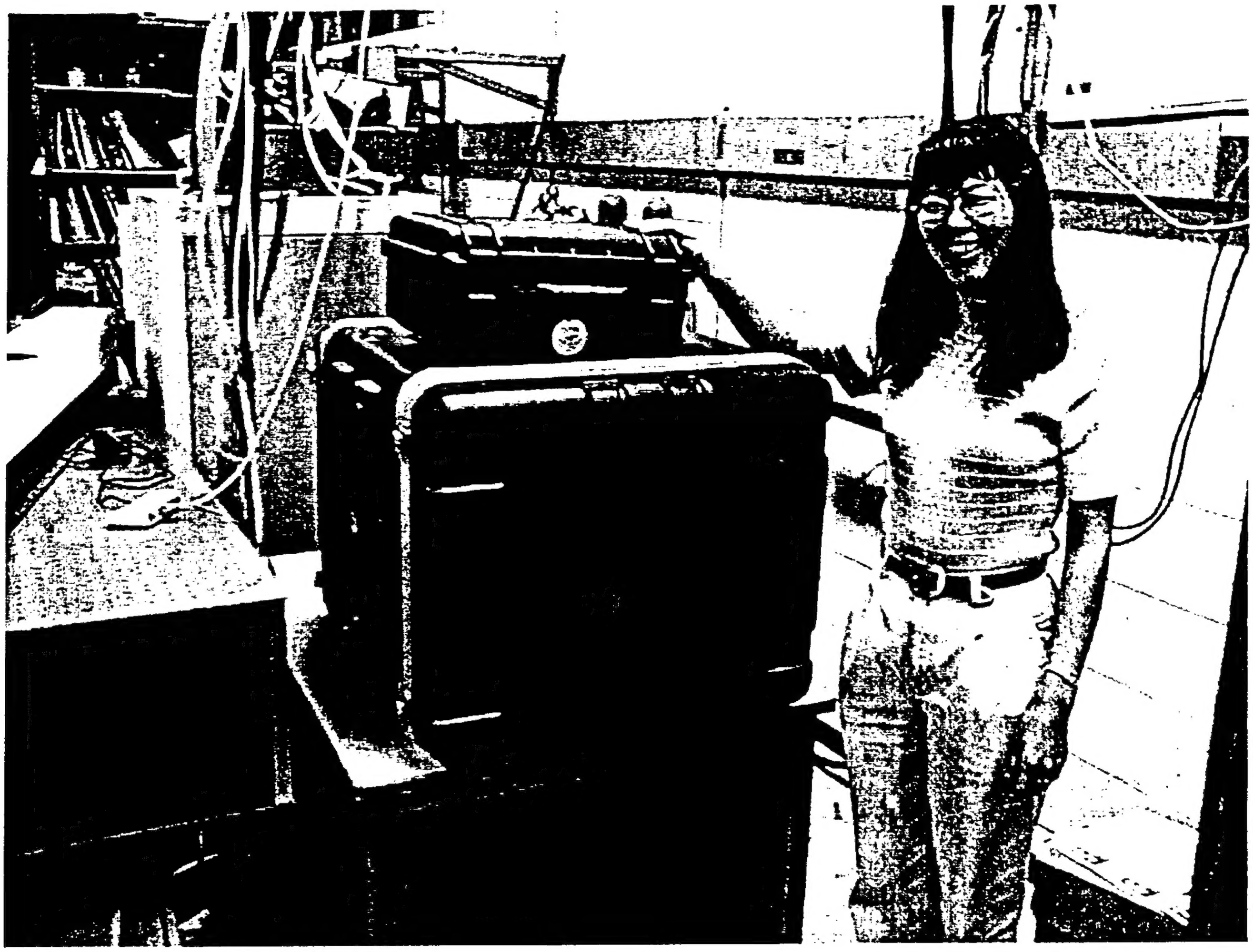


Fig. 4 Photograph of the system, shown packed and ready for shipment, with camera in its shipping case, which can be hand-carried for safety.

Example Application: Detection of Subsurface Corrosion in Aircraft Structures

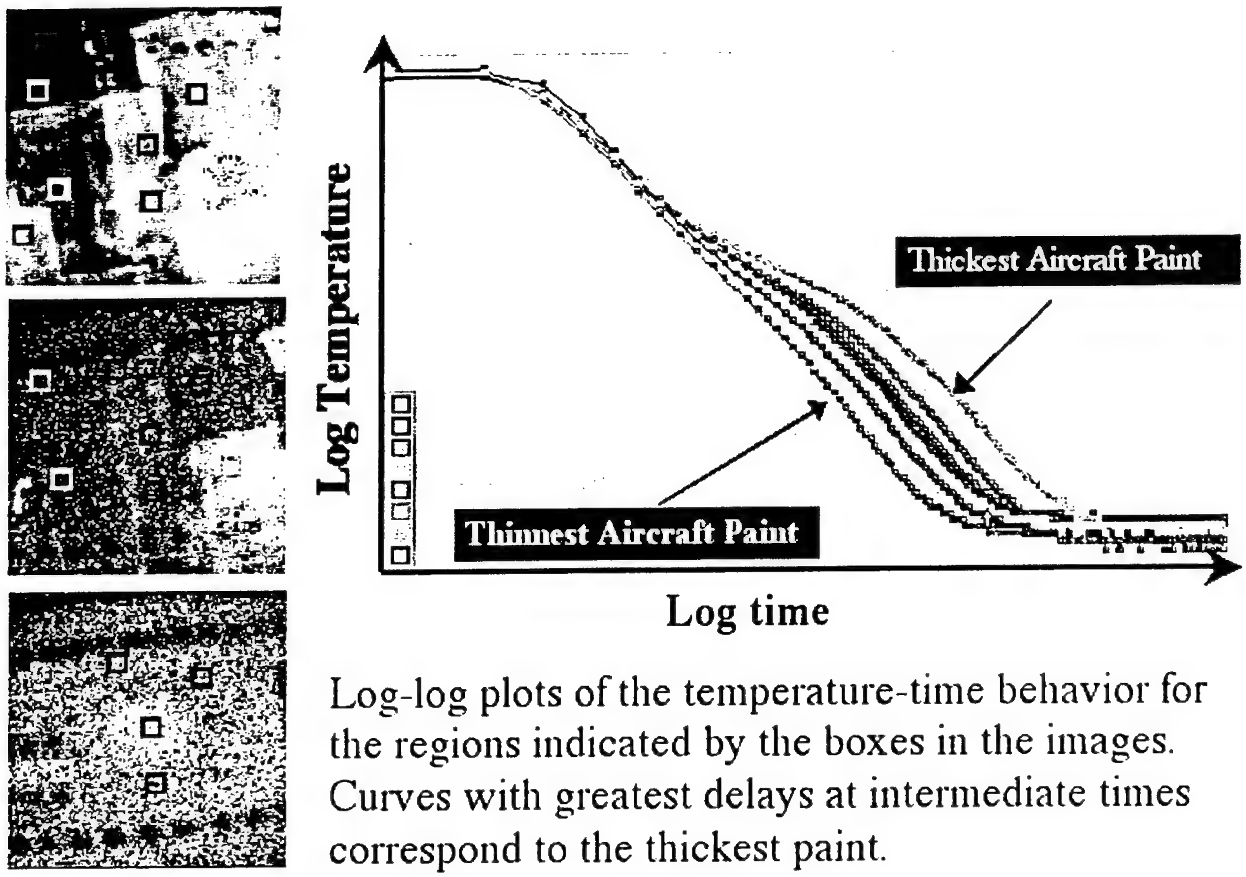


Fig. 5 Thermal wave images (left) at progressively later times (top to bottom) after the flash on a region of belly skin on a DC-9 aircraft that had multiple layers of paint. The log-log plot shows the temperature-time behavior for regions (indicated by squares in the images) over various paint thicknesses, plus a (central) region of rear-surface skin corrosion. The thicker paint yields longer time delays, and both paint thickness and metal corrosion loss can be determined by our thermal wave algorithm that utilizes the temperature-time profile. The results of a blind test of rear surface corrosion on this DC-9 aircraft are shown in Fig. 6.

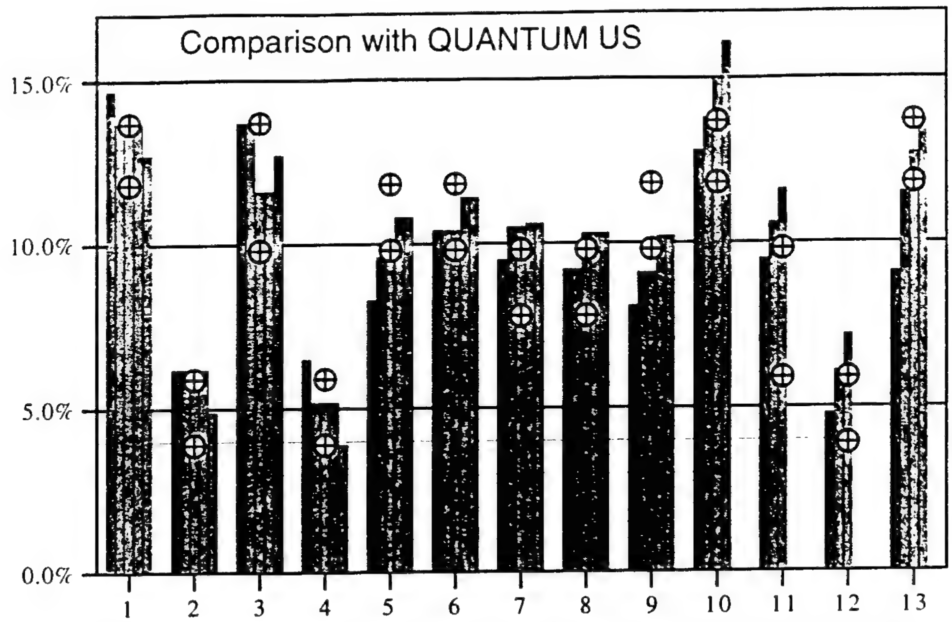


Fig. 6 Results of a blind test of rear surface corrosion on the DC-9 aircraft showing a comparison between our thermal wave algorithm predictions (vertical bars), and the independently measured ultrasonic results (circles). We detected all thirteen of the test areas, with no false calls, and our quantitative measurements of percentage corrosion loss were in good agreement with the point by point ultrasonic measurements.

Example Application: Thermosonic Crack Detection

Attached is a reprint of a recent article, "Infrared imaging of defects heated by a sonic pulse," by L.D. Favro, Xiaoyan Han, Zhong Ouang, Gang Sun, Hua Sui, and R.L. Thomas, published in Review of Scientific Instruments, Volume 71, Number 6, June 2000, pp. 2418-2421. We believe that this exciting new NDE technology will make extensive and effective use of the High-Speed, High-Resolution Focal Plane Array Imaging System described here. The high speed is an advantage, because the images of cracks appear just milliseconds after the initiation of the sound pulse (see attached reprint). High frame rates allow the capture of the details of the crack size and shape before lateral heat diffusion blurs the image. The high resolution provides two advantages. First, when backed off, it can inspect wide areas for locating any possible cracks in a very short time. Second, when zoomed in, it can image very small cracks with high spatial resolution.

The necessity for finding extremely small cracks was emphasized by Dr. Thomas Moran of Wright Patterson Air Force Base when he visited our laboratories several weeks ago. He pointed out

that the Engine Rotor Life Extension (ERLE) program required finding cracks whose dimensions would be measured in microns, not the tens of mils which is the current practical limit of conventional crack detection methods. Accordingly, he brought with him two titanium fatigue test bars, one with a 54 micron (2 mil) crack, and one with a 20 micron (less than 1 mil) crack. Both cracks were successfully imaged using our thermosonic system, as shown in Fig. 7 below. As a result, we have been asked by Universal Technology Corporation, on behalf of WPAFB, to submit a proposal to evaluate thermosonics for detecting 50 to 100 micron cracks under fretting, and to explore the feasibility of imaging cracks in engine rotor dovetail areas. That proposal has just been submitted and we expect a positive response to it. We anticipate that the new camera will play a very important role in this program.

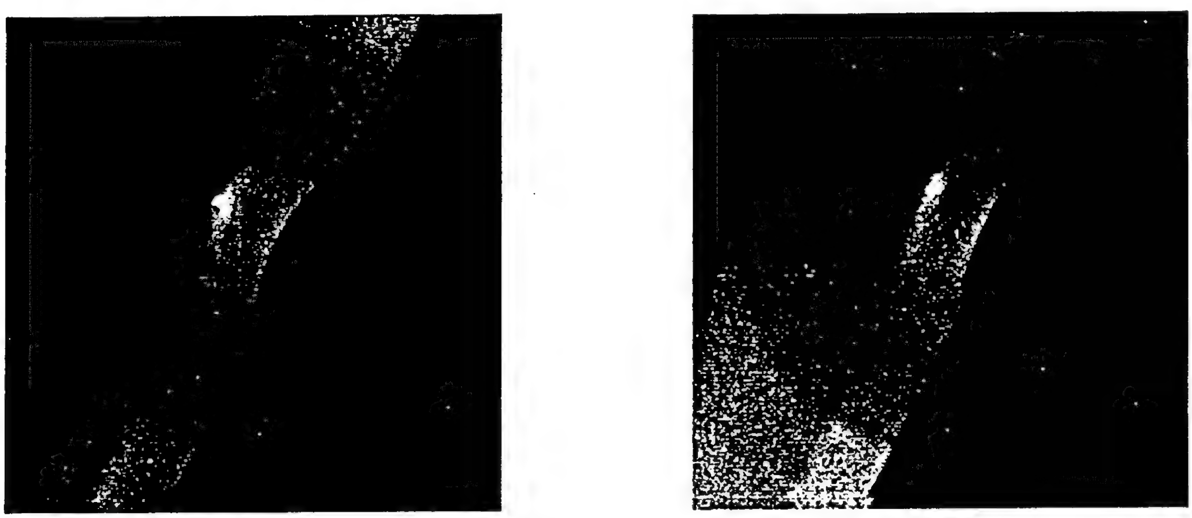


Fig. 7 Thermosonic images of a 50 micron long crack (left) and a 20 micron long crack (right) in titanium test bars supplied to us by Dr. Tom Moran of WPAFB.

Budget Summary

The Revised Budget for the Imaging System is shown below in Table 1. As noted earlier in this report, the vendor was subsequently changed to Indigo Systems, Inc., with no change in the overall costs for the system, nor the distribution between AFOSR and WSU. The expenditures and cost-sharing distribution for the delivered Imaging System are listed in Table 2. A separate formal Final Accounting Report will be submitted by the WSU Accounting Department.

TABLE 1 – REVISED BUDGET

ITEM	Part No.	Description	Price
		Raytheon Amber	
	ResolveIR'	Large-format MWIR InSb Camera	$175,000
	50398-SP	50-foot Power/Interface Cable	$1,100
	504022-03	50-foot High-Speed Video Bus Cable (Digital)	$500
	250-TBD	13 mm EFL MWIR Lens for Large Format	$25,000
	250-9032	25 mm EFL MWIR Lens for Large Format	$13,500
		Sub-total	**$215,100**
		Thermal Wave Imaging, Inc. [Note 1]	
	TBD	Electronic Hardware/Software for TWI	**Deleted**
		Sub-total	**$0**
		TOTAL EQUIPMENT BUDGET	**$215,100**
		WAYNE STATE UNIVERSITY COST-SHARING	**$105,100**
		FUNDS REQUESTED FROM DURIP	**$110,000**

TABLE 2 – EXPENDITURES

Requisition/P.O. No.	Vendor	Description	AFOSR	WSU
G002144	Indigo Systems, Inc.	Camera System	$108,050	$0
R443974	Indigo Systems, Inc.	Processing Unit, System Integration	$1,950	$66,100
R476916	Indigo Systems, Inc.	Sunlight Readable Monitor		$8,052
TE 44905, TE 44906, TE4490	Travel Expenses	Meeting with Vendors		$2,262
R477345	Janos	IR Lenses		$7,045
P246576	Diop	IR Lenses		$12,360
R447977	Indigo Systems, Inc.	Electronic Hardware& Software		$9,660
			$110,000	**$105,479**

Reference

1. L.D. Favro, Xiaoyan Han, Zhong Ouang, Gang Sun, Hua Sui, and R.L. Thomas, *Rev. Sci. Instr.*, **71**, Number 6, June 2000, pp. 2418-2421.

Appendix: Quote from Indigo/Lumitron

Dr. Robert Thomas
Director, Institute for Manufacturing Research
Wayne State University
281 Physics Research Building
Detroit, MI 48202

Subject:

Indigo / Lumitron Large Format IR Camera Proposal

Reference:

Quote Number **990303**

Dear Bob,

Indigo Systems Corp. and Lumitron Inc. are pleased to offer this proposal to Wayne State University in support of the Institute for Manufacturing Research s project for imaging of aircraft structures. This proposal describes the camera components and how these components will be integrated into a turn-key system.

PROJECT PARTICIPANTS
The project effort will be supported by two companies: Indigo Systems Corp., (Santa Barbara, CA); and Lumitron, Inc. (Louisville, KY). Indigo and Lumitron have a close working relationship for the development of multiple IR camera products.

INDIGO SYSTEMS
Indigo is a small, employee-owned business. Approximately three-fourths of Indigo s 36 employees were formerly employed by Amber Engineering, including all of Indigo s principal shareholders, as well as many of the engineers involved in the development of the Radiance camera. Indigo is committed to customer satisfaction, and is unfettered by the bureaucracy inherent in a large or a parent company.

INDIGO PRODUCTS & CAMERA DEVELOPMENT PATH
Indigo specializes in readout integrated circuit (ROIC) design & testing. Besides the custom ROIC programs, Indigo offers several ROIC designs as standard products. Two of these designs are the ISC9705 and the ISC9803. Both of these ROICs utilize snapshot (simultaneous) mode detector integration.

The ISC9705 is a 320x240 format readout device with a detector pitch of 30 microns that is compatible with Indium Antimonide (InSb), Indium Gallium Arsenide (InGaAs), and QWIP detectors. Indigo is producing a family of moderately priced, 12-bit digital-capable infrared cameras, called *Merlin,* that is based on the use of these different detector types. This flexibility in readout technology enables, for the first time, stan-dard camera configurations to be offered that operate over the three primary IR wave-bands of interest: near IR (InGaAs); midwave IR (InSb); and longwave IR Quantum Well Infrared Photodetectors (QWIPs).

The ISC9803 is Indigo s standard 640x512 format readout circuit, with a pixel pitch of 25 microns. This ROIC is compatible with the same multiple detector materials as the ISC9705. Indigo plans to develop a series of IR cameras that will use the ISC9803 to achieve the higher display resolutions required by many applications.

LUMITRON

Lumitron is a small, employee-owned business. 25% of Lumitron s employees were formerly employed by Amber Engineering, including the Radiance s system engineer Jeff Metschuleit.

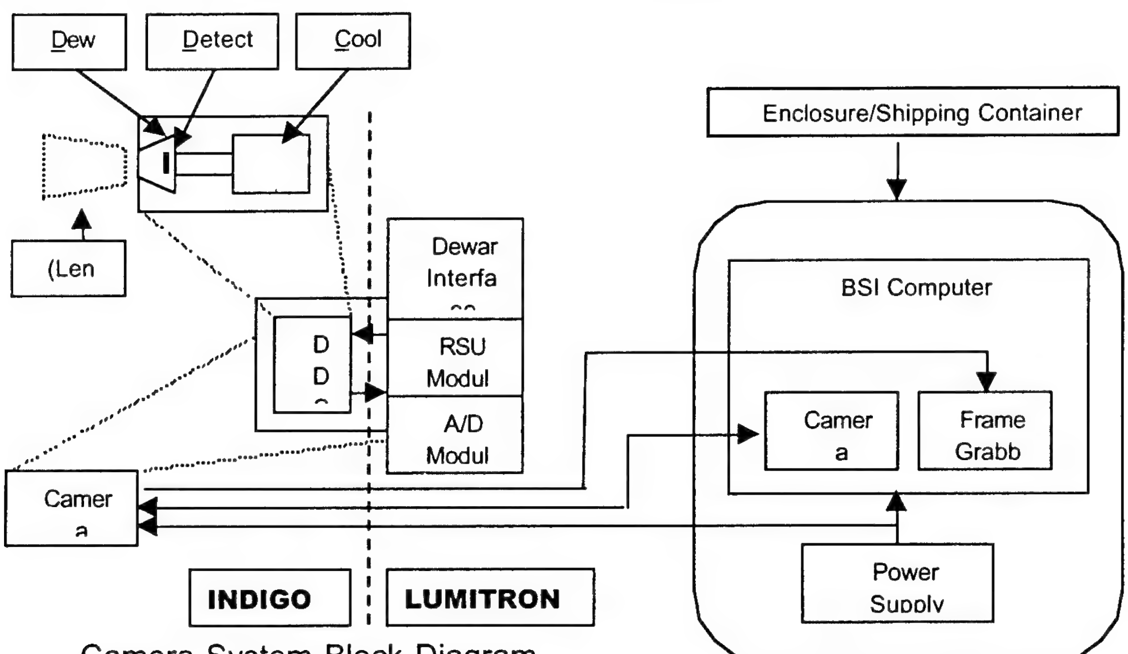
LUMITRON PRODUCTS

Lumitron designs and produces highly reliable, compact, and easy to use imaging electronics for the infrared community. Lumitron has formulated a "Virtual Factory" business structure with diversified component suppliers to handle volume production while maintaining an internal capability to design, fabricate, assemble, and test electronic products and associated software to deliver product in small quantities.

Years of experience have demonstrated to Lumitron s development staff that ease of use for an IR imaging system is absolutely essential. Lumitron has designed their SVS-2000 product to be upgradeable with both electronics and software such that the basic system will never become obsolete and customers need not re-invest with each advance in focal plane technology. Lumitron maintains a software staff, and as an option provides source code and a developers kit with SVS-2000 systems.

PROJECT OVERVIEW

A large format mid-wavelength infrared (MWIR) camera system will be developed. A functional block diagram of the camera system is shown below:



Camera System Block Diagram

The camera system consists of two assemblies, the camera head, and the processing unit. The camera head contains the FPA/dewar/cooler assembly and the remote support electronics. The processing unit contains a portable PC with monitor, and the camera head power supply.

INDIGO STATEMENT OF WORK
Indigo will develop a large format infrared camera head based on a standardized, high-performance readout integrated circuit design, the ISC9803. The camera head will accept existing bayonet-mount optics, and will be compatible with processing electronics available from Lumitron Inc. The camera head will be optimized for man-portable operation -- total weight of the camera head is less than 5 lbs.

Focal Plane Array
The camera sensor is an ISC9803 640x512-based Indium Antimonide (InSb) focal plane array (FPA). The unit cells are on a 25x25 micron pitch. The design provides advanced features such as flexible integration control, dynamic image transposition, dynamic windowing, multiple outputs, and variable gain. For Wayne State s application, the FPA is operated in a 4-output mode to achieve maximum frame rates and windowing options. Each FPA output is rated at 10 MHz operation, although higher rates may be possible as better A/D converters and frame grabbers become available.

Sensor Engine
An ISC9803 InSb FPA will be integrated with a dewar and high-reliability closed-cycle cooler to form a sensor-engine subassembly. The cooler is a miniature integral type that is approximately one-half the size and weight of split-stirling coolers of equivalent cooling capacity. The sensor engine will be integrated along with remote support electronics into an enclosure designed for hand-held and/or tripod mounted operation.

Optical Configuration
The optical design of the camera will be f/2.5. The coldfilter material will be sapphire, and the dewar window will be germanium. The camera will incorporate a standard bayonet flange that will accept standard bayonet-mount lenses.

Ergonomics
The camera head will be designed to be as small and lightweight as possible, to accommodate hand-held use. The total weight of the camera head will be less than 5 pounds, and average power dissipation less than 25 watts. The camera head will be cooled via an internal fan to minimize heat transfer through the camera chassis, such that the unit may be held comfortably with bare hands.

LUMITRON STATEMENT OF WORK

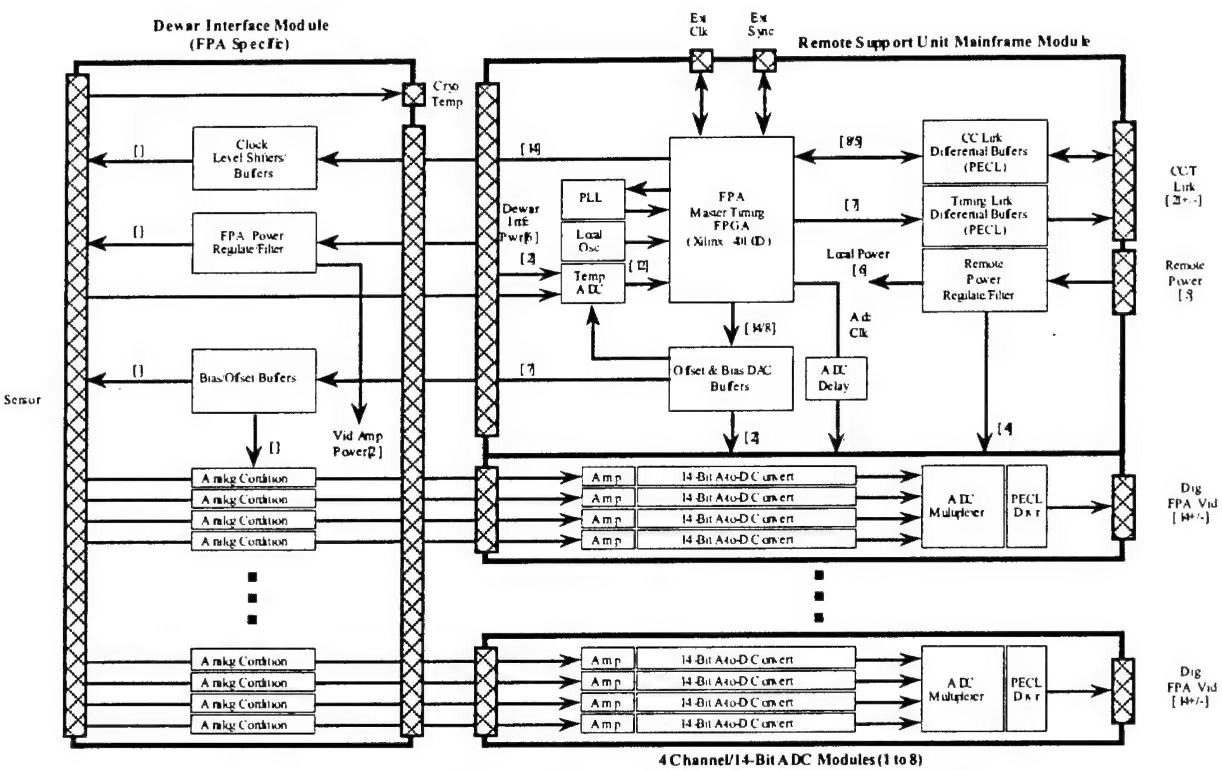
Lumitron will build a processing unit based on a Broadax Systems Inc (BSI) Portable PC containing an Imaging Technology IC-DIG frame grabber, and a Lumitron designed camera head Interface Module. The camera software runs under the Windows NT operating system. The portable PC and camera head power supply are mounted in a ruggedized 19 inch rack mount enclosure which also functions as a shipping container. The rackmount enclosure will have space for customer furnished hardware if required. The total weight of this assembly excluding customer-furnished hardware is less than 80 lbs.

Remote Support Electronics Description

The Remote Support Electronics provides timing and bias to the FPA, conditions and digitizes its outputs, and allows user adjustment of various parameters. A block diagram of the Remote Support Electronics is shown below:

The Remote Support Electronics consists of the following four printed circuit boards:

1. Dewar Interface Module
2. 4 Channel A/D Module
3. RSU Mainframe Module
4. Power Supply



Generic Digital Remote Support Unit Block Diagram

Dewar Interface Module
The Dewar Interface Module contains the FPA bias supplies, clock drivers, and video preamplifiers. This board is mounted as close to the dewar assembly as possible to minimize noise pickup. The design of this board is specific to the FPA and dewar used, the dewar electrical interconnect cable plugs into the Dewar Interface Board. The Dewar Interface Module in turn plugs directly into the 4 Channel A/D Module. Minimizing the distances between dewar, Dewar Interface Module, and 4-channel A/D Module is critical in maintaining the low noise level required in 14-bit systems. The Dewar Interface Module will be specifically designed for Indigo s ISC9803 FPA.

4 Channel A/D Module
The 4 Channel A/D Module contains four 10MHz 14 bit A/D converters and an FPGA configured as a 4-to-1 digital multiplexer. The module is part of a standard Lumitron Generic Digital Remote Support Unit and will be used as is for the large format camera. The A/D input range is under software control and is adjustable by the user. The output of this module is a differential 14-bit data stream that is sent to the Processing Unit via a multi-conductor cable. Future growth to FPAs having more than 4 outputs is possible by stacking multiple 4-channel A/D Modules one on top the other via board stacking connectors.

RSU Mainframe Module
The RSU Mainframe Module contains the master timing FPGA that generates FPA timing signals along with other signals required by the camera head electronics. Additional command and control functions for the FPA and 4-channel A/D modules as well as power conditioning and user adjustable biases are also generated in the RSU Mainframe Module. The RSU Mainframe Module is connected to the Processing Unit via a multi-conductor Command Control/Timing Link. The RSU Mainframe Module is part of a standard Lumitron Generic Digital Remote Support Unit and will be used as is for the Large Format Camera.

Power Supply Module
The Camera Head receives 28-Volt power from a power supply in the Processing Unit. The raw 28-Volt input power is filtered and converted to the various voltages needed by the Camera Head by a DC-to-DC converter and linear regulators located in the Camera Head Power Supply Module.

Processing Unit Electronics Description
The Processing Unit is based on a portable lunch box computer manufactured by Broadax Systems Inc (BSI). The BSI FieldGo PX computer features a 450MHz Pentium II CPU (or better) running the Windows NT Operating System. The com-puter contains a Lumitron designed Camera Head Interface Module and an Imaging Technology IC-DIG video frame grabber card. These cards will occupy two of the computer s ISA card slots. The computer will be fitted on a slide out 19-inch rack mount drawer assembly, allowing it to be mounted in a wheeled rack mount enclo-sure which also functions as a shipping container. Also mounted in the enclosure is a 28 volt power supply for the Camera Head and any customer supplied hardware. The amount of customer supplied hardware will

determine the ultimate size and weight of the Processing Unit, the goal is to keep the total system weight under 80 lbs.

Computer Description

The BSI FieldGo PX computer is a portable unit ruggedized for industrial applications. The BSI FieldGo PX Computer measures 15.7 W x 13.1 H x 9.2 D and weighs approximately 30 pounds. The computer has the following features:

- 450 MHz Pentium II Processor
- 1 Gb System Memory
- 18.0 Gb SCSI-Wide Hard Disk Drive
- 15.1 XGA (1024x768) TFT Display
- 8Mb AGP Video Card
- Iomega Jazz 2.0Gb Internal SCSI Drive
- 1.44 Mb Floppy Drive
- Windows NT Operating System
- 300W 110/220 Power Supply

Camera Head Interface Module Description

The Lumitron designed Camera Head Interface Module transmits and receives signals from the Camera Head via the Command Control/Timing (CC/T) Link. The Module occupies a single expansion slot in the BSI FieldGo computer. An FPGA within the Module provides the interface between the computer s processor bus and the CC/T link.

Imaging Technology IC-DIG Frame Grabber

The Imaging Technology IC-DIG Frame Grabber is a half-slot PCI card that receives RS-422 differential digital video from the Camera Head and transfers it to the computer s system memory. The IC-DIG frame grabber as configured for this application has a 40 MSPS maximum data transfer rate which matches the maximum conversion rate of the four 14 bit A/D s. The standard video memory size is 2Mb which allows up to a 1K x 1K FPA format.

Processing Unit Software

The Camera system is controlled by Lumitron developed software running on the Windows NT operating system. A GUI based configuration manager allows interactive manipulation of various FPA functions. Up to 16 operational modes may be preconfigured to accommodate different FPA window sizes, multiple integration times, multiple frame rates, etc. A software developer s kit is available which includes hardware register documentation as well as source code for the control executable software. The software is generated using Microsoft Visual C++.

SYSTEM INTEGRATION AND ACCEPTANCE TESTING

Lumitron, with assistance provided as required from Indigo, will integrate the camera head and remote support electronics. A multi-conductor cable up to 50 feet long will be furnished to link the camera head with the processing unit. An Acceptance Test Report will be delivered with the camera system.

PROJECT SCHEDULE

Delivery schedule for the camera system is November 30, 1999, assuming contract authorization is received by March 30, 1999.

PRICE QUOTATION

Responsibility	Item Description	Price
Indigo	Camera Head	$108,000
Lumitron	Processing Unit, System Integration	$68,000
	Total:	**$176,000**

Separate purchase orders to Indigo and Lumitron will reduce the system cost by negating the need for one company to act as a prime contractor and burden the other s costs with G&A and overhead.

WARRANTY

The camera system will be warranted for a period of one year from the date of initial delivery.

TERMS

Payment terms are Net 30, FOB manufacturer s facility. This bid is based on the use of Indigo s and Lumitron s Standard Terms and Conditions.

We look forward to working with the Institute for Manufacturing Research on this project. Please contact the undersigned with any questions concerning this proposal.

Sincerely,
FOR INDIGO SYSTEMS

Stan Laband

Stan Laband
Account Manager

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Web: www.indigosystems.com

Infrared imaging of defects heated by a sonic pulse

L. D. Favro
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Xiaoyan Han
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High-frequency pulsed sonic excitation is combined with an infrared camera to image surface and subsurface defects. Irreversible temperature increases on the surface of the object, resulting from localized heating in the vicinity of cracks, disbonds, or delaminations, are imaged as a function of time prior to, during, and following the application of a short pulse of sound. Pulse durations of 50 ms are sufficient to image such defects, and result in surface temperatures variations of ~2 °C above the defect. As an example, sonic infrared images are presented for two fatigue cracks in Al and of interply delamination impact damage in a graphite–fiber-reinforced polymer composite. The shorter of the two fatigue cracks is ~0.7 mm in length, and is tightly closed. Thus, this new technique is sensitive, and capable of rapid imaging of defects under wide surface areas of an object. © *2000 American Institute of Physics.* [S0034-6748(00)05006-1]

I. INTRODUCTION

We describe a novel nondestructive testing technique that uses high-frequency sonic excitation, together with infrared (IR) detection to image surface and subsurface defects.[1] This sonic IR imaging technique uses a short (50–200 ms) pulse of high frequency (typically 20–40 kHz) sound which is applied at some convenient point on the surface of the object under inspection to produce localized frictional heating at the defect. An IR camera images the heating of the surface resulting from the effects of friction or other irreversible internal surface interactions in the vicinity of cracks or disbonds. These effects result from the fact that the two surfaces of internal defects do not move in unison when sound propagates in the object. Thus, for instance, the faying surfaces of a closed crack appear as a planar heat source. If the crack intersects the surface, the heat source first appears as a line in the IR image, which subsequently blurs and broadens into a diffusely heated region surrounding the original line. When the sound pulse is turned off, the resulting temperature pattern decays according to the usual process of thermal diffusion.

Although this new process superficially resembles stress pattern analysis by thermal emission (SPATE),[2] SPATE depends on periodic thermoelastic temperature variations, with synchronous detection (at the vibration frequency) of these temperature variations associated with the sinusoidal stress-induced heating and cooling. In contrast, the 20 kHz thermoelastic heating and cooling variations associated with our sonic pulse are averaged out over the 1 ms (or so) integration time of the IR camera. Thus, only the irreversible temperature increases are imaged by our camera.

Our technique more closely resembles one introduced by Busse and his colleagues.[3] Busse also utilized sonic excitation and IR imaging. His technique, rather than using a single sound pulse, instead utilized very low frequency (a few tens of milliHertz) sinusoidal amplitude modulation of the acoustic source, coupled with video lock-in IR imaging at that very low frequency. Lock-in averaging at the modulation frequency produces two processed images: an amplitude image and a phase image. Because of the low modulation frequency, typically several minutes are required to produce these processed lock-in images. In contrast, our single-pulsed technique requires only a few tens of milliseconds to acquire a sequence of images of the entire time evolution of the heating process. To acquire the same temporal information, the lock-in imaging would have to be repeated over and over again for a range of different modulation frequencies.

II. EXPERIMENT

Our experimental setup is shown in Fig. 1. The source of the sonic excitation is a Branson, Model 900 MA 20 kHz ultrasonic welding generator, with a Model GK-5 hand-held gun. The source has a maximum power of 1 kW, and is triggered to provide a short (typically 50–200 ms duration) output pulse to the gun. The gun contains a piezoelectric transducer that couples to the specimen through the 1.3-cm-diam tip of a steel horn. In the laboratory setup, as can be seen in Fig. 1, we use a mechanical fixture to hold the sonic horn firmly against the sample surface. This setup uses a machine slide to provide reproducible alignment of the horn. Typically, a piece of soft Cu sheet is placed between the tip of the horn and the specimen to provide good sound transmission. The location of the source on the sample is chosen primarily for convenience of geometrical alignment, and since it has minimal effect on the resulting sonic IR images,

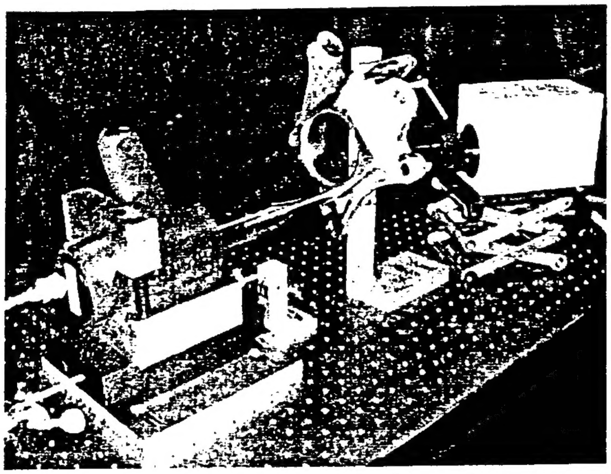

FIG. 1. Experimental arrangement for sonic IR imaging of defects. A hand-held ultrasonic welding gun is seen, mounted on a machine slide for ease of alignment, and is pressed against a part by means of a pulley and rope system. The IR camera is positioned for a closeup view of the rear of the part. Wider fields of view are obtained by simply backing up the camera and/or using different IR lenses.

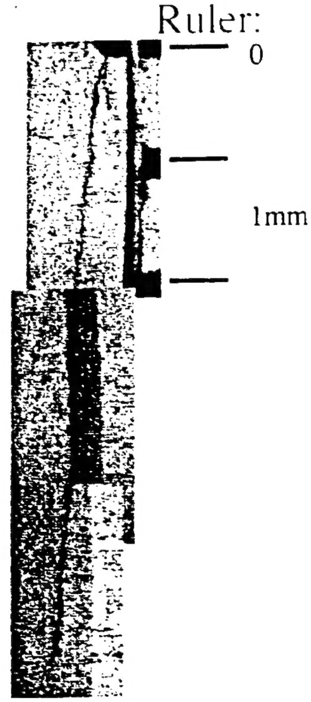

FIG. 2. Optical micrograph of a fatigue crack in a 3-mm-thick aluminum alloy bar. The bottom edge of the saw cut used to initiate the crack is seen (black) just above the top of the crack, which is approximately 5 mm long.

typically is not changed during the course of the inspection. Sound waves at frequencies of 20 kHz in metals such as aluminum or steel have wavelengths on the order of tens of centimeters, and propagate with appreciable amplitude over distances much longer than a wavelength. For typical complex-shaped industrial parts (see, for example, the aluminum automotive part shown in Fig. 1), reflections from various boundaries of the specimen introduce countless conversions among the vibrational modes, leading to a very complicated pattern of sound within the specimen during the time that the pulse is applied. Since the speed of sound in solids is typically on the order of a few km/s, this sound field completely insonifies the regions under inspection during the time that the excitation pulse is applied. If a subsurface interface is present, say a fatigue crack in a metal, or a delamination in a composite structure, the opposing surfaces at the interface will be caused to move by the various sound modes present there. The complexity of the sound is such that relative motion of these surfaces will ordinarily have components both in the plane of the crack and normal to it. Thus, the surfaces will "rub" and "slap" against one another, with a concomitant local dissipation of mechanical energy. This energy dissipation causes a temperature rise, which propagates in the material through thermal diffusion. We monitor this dissipation through its effect on the surface temperature distribution. The resolution of the resulting images depends on the depth of the dissipative source as well as on the time at which the imaging is carried out.

The IR camera that we used in the setup that is shown in Fig. 1 is a Raytheon Radiance HS that contains a 256×256 InSb focal plane array, and operates in the 3–5 μm spectral region. It is sensitive (with a 1 ms integration time) to surface temperature changes of ~0.03 °C, and can be operated at full frame rates up to 140 Hz with that sensitivity. We have also observed the effects reported here with a considerably less expensive, uncooled, microbolometer focal plane array camera, operating in the long wavelength (7–10 μm) of the IR.

III. RESULTS

We first illustrate the use of this technique to image a 5-mm-long fatigue crack in an aluminum plate. The plate (3 mm thick) had been prepared with a saw cut in the middle of one of its edges prior to being fatigued in a cyclic-loaded mechanical tensile testing machine. An optical micrograph of the resulting fatigue crack is shown in Fig. 2, which also shows a ruler with 1 mm calibration marks. The crack is about 5 mm long. Figure 3 shows a selection from a sequence of sonic IR images of this specimen that were acquired prior to, during, and immediately after the application of the excitation pulse. It is evident from this sequence of images that such cracks are easily detected by the technique. The temperature contrast in this image is ~2 °C. In Fig. 4, we show an optical micrograph of a much shorter (0.7-mm-long) fatigue crack in a second such Al test specimen. We show a selection of sonic IR images in Fig. 5 of the crack that was shown optically in Fig. 4. This set of images illustrates that rather small cracks are readily detected by the technique.

In order to demonstrate that the thermal effects seen in Figs. 3 and 5 are not simply the result of the presence of the stresses around the tip of the saw cuts used to initiate the fatigue cracks, we introduced a second saw cut in a third fatigue specimen after the fatigue crack had been grown from the first saw cut. It can also be seen in the images shown in Fig. 6 that two saw cuts are present in the top of the specimen. The right saw cut was placed in the specimen

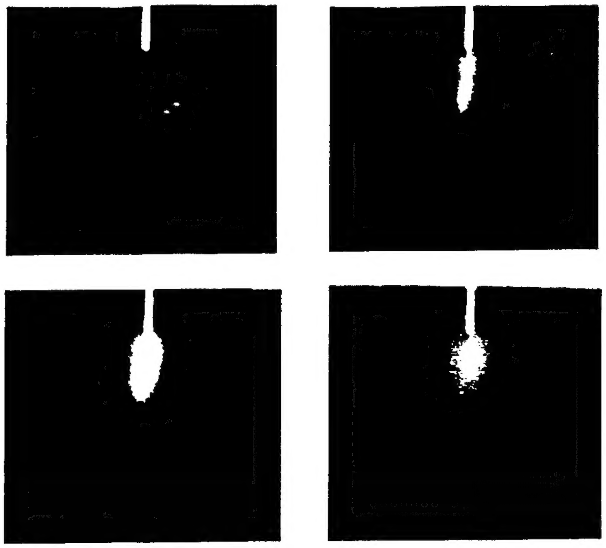

FIG. 3. Selection of four frames from a sequence of sonic IR images of the crack shown optically in Fig. 2 above. The top left image was taken prior to turning on the sonic excitation, the top right was taken immediately following the initiation of the pulse, and the bottom left and right images were taken at two later times, during and immediately after the 50 ms sonic excitation, respectively.

prior to fatigue, and the resulting crack (0.8 mm long) was initiated at the bottom of this cut. The left saw cut is the one that was placed in the specimen after the fatigue, and there is no crack in this region of the specimen. It should be noted that the only the sonic IR response is located in the vicinity of the fatigue crack (beneath the right saw cut). This illustrates the fact that the effect is not the result of thermoelastic temperature variations in the high stress region in the vicinity of the tip of the saw cut.

As another illustration, we have applied the sonic IR technique to inspect a graphite–fiber-reinforced polymer

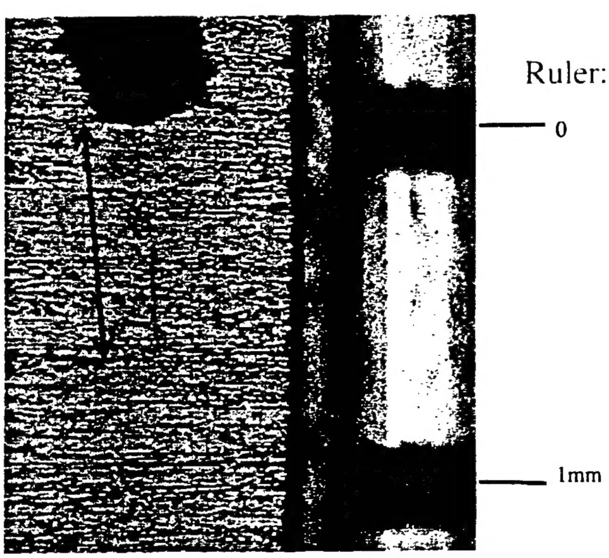

FIG. 4. Optical micrograph of a fatigue crack in a 3-mm-thick aluminum alloy bar. The bottom edge of the saw cut used to initiate the crack is seen (black) just above the top of the crack, which is approximately 0.7 mm long and closed.

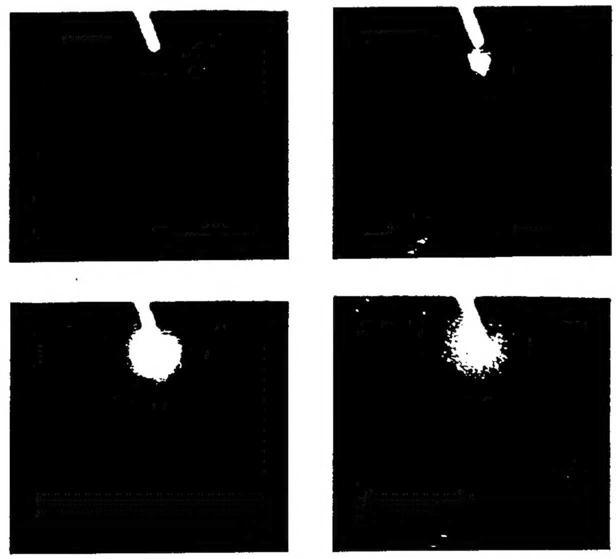

FIG. 5. Selection of four frames from a sequence of sonic IR images of the crack shown optically in Fig. 4 above. The top left image was taken prior to turning on the sonic excitation, the top right immediately following the excitation pulse, and the bottom left and right images taken at two later times during the 50 ms sonic excitation.

composite laminate specimen that had previously been subjected to impact damage. The resulting damage occurs in the form of interply delaminations. These delaminations are effectively cracks, oriented parallel to the plane of the sample surface, and serve as heat sources under sonic excitation. In Fig. 7, we compare thermal images of the delaminations in this sample, made both with conventional pulsed thermal wave imaging under flash lamp heating and sonic IR imaging. Both sets of images were made in our laboratory. The times of the pairs of images were selected to correspond as nearly as possible to the same stage of development of the two images. The sonic IR images clearly show more detail of the subsurface features than do the thermal wave images.

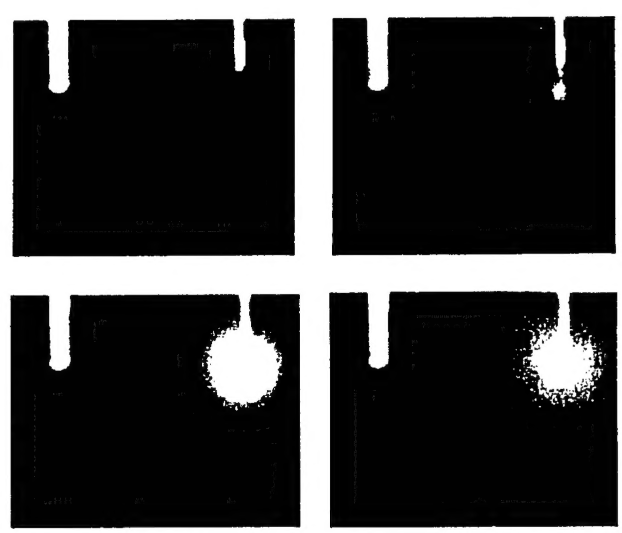

FIG. 6. Selection of four frames from a sequence of sonic IR images of a fatigue specimen containing two saw cuts, but with only one (right) having been used to initiate a fatigue crack.

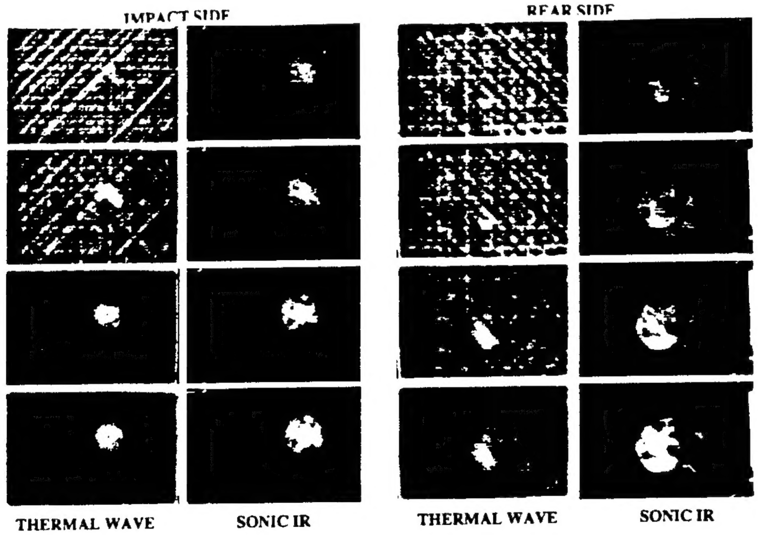

FIG. 7. Comparison of thermal wave images with sonic IR images of a thick (1.1 cm) graphite fiber reinforced laminated composite slab containing interply delaminations from impact damage. The four rows of images were taken at progressively later times following flash (surface) or sonic (internal) heating. The left pair are images taken from the impact side, and the right pair from the rear side.

This results, in part, from the fact that the thermal wave images are seen against a bright background of the flash-heated surface, whereas the sonic IR images are seen against a dark field. A second factor is that tightly closed delaminations (''kissing disbonds'') present very small thermal reflection coefficients to the incident thermal waves, but serve as efficient sources of heat under sonic excitation. Furthermore, the thermal wave images exhibit much more clutter due to local variations in thermal diffusivity of the fibers, etc., as can be seen most prominently in the early time images, whereas in the sonic IR images, only the variations in the heat source at the excited defect are seen.

IV. DISCUSSION

For many practical applications, this new sonic IR imaging technique has significant advantages over both other thermal imaging methods and traditional nondestructive inspection methods. It is fast, wide area, and sensitive to cracks with any geometrical orientation, and unlike for example, magnetic particle inspection, is not restricted to particular classes of materials.

[1] Patent Pending, Wayne State University.
[2] See, for example, Zhang, Daqing, Sandor, and I. Bela, ASTM Spec. Tech. Pub., 1992, p. 428.
[3] J. Rantala, D. Wu, and G. Busse, Res. Nondestruct. Eval. 7, 215 (1995).